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Chapter 2

APPROPRIATE AND SUSTAINABLE WATER DISINFECTION METHODS FOR DEVELOPING COMMUNITIES

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ABSTRACT

Safe drinking water is a critical need in developing communities around the globe. A variety of disinfection methods can be used at a community scale or as household water treatment. It is important that such methods are appropriate and sustainable for the environmental, economic, and societal constraints of each setting. This chapter highlights some of the methods commonly used in developing communities and compares their documented disinfection effectiveness in laboratory tests and field use. The strengths and weaknesses of each approach in regards to the removal and/or inactivation of bacteria, viruses, and protozoans are compared. Community scale methods reviewed include slow sand filtration, riverbank filtration, and solar-based approaches. Commonly used household treatment methods, also called point-of-use (POU) treatment, that are reviewed include chemical treatment, biosand, ceramic water filters, and solar disinfection. Global application of POU methods is increasing, but their long-term use and effectiveness is generally poorly documented. Many of these methods are undergoing increasing levels of research, but performance differences between the lab and field studies are a concern. A few studies have also documented health benefits associated with the use of these treatment methods; however, more research of this type is also needed.

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1. INTRODUCTION

Globally there is a desperate need for simple, low cost methods to disinfect drinking water. It has been estimated that more than 1 billion people do not have access to clean water. It has also been estimated that about 40% of the global population lives on less than $2/day and about 1 billion people live on less than $1 per day (World Bank Development Indicators 2008). The United Nations Millennium Development Goals include a number of targets that relate to water (such as reducing childhood mortality, which may be caused by water-borne illness). More specifically, in Goal 7 to ensure environmental sustainability, a specific target was to reduce by half the proportion of people without sustainable access to safe drinking water. It has been estimated that achieving this goal will cost $10-$30 billion more than the amounts already being spent. (http://www. unesco. org/water/wwap/ facts_figures/mdgs. shtml).

This paper reviews low cost technologies that may be appropriate to disinfect water. These treatment approaches have been grouped into two general categories: (1) community scale and (2) household or point-of-use treatment methods. This review is not exhaustive but is intended to highlight widely used methods, a few emerging promising technologies, and recent data on the effectiveness of these treatment methods. For each method the information provided includes: prevalence of use, water yield, cost, a basic technical description, concerns/limitations, and reported disinfection efficiency.

Disinfection of water requires the removal of pathogenic viruses, bacteria, protozoans, and parasites. Complete characterization of the microbial community within water is expensive and time consuming, so indicators are commonly used. For bacteria, total coliform and *E. coli* are the most common indicators. For viruses, phage are often used. Due to the simplicity of enumeration, coliphage are common. MS2, a male specific coliphage, is the most commonly tested surrogate used to characterize drinking water disinfection. For protozoans, *Giardia lamblia* cysts (*Giardia*) and *Cryptosporidium parvum* oocysts (*Crypto*) are commonly used. Although there are recognized limitations to the use of indicator species, their results for disinfection are reported here to compare the performance of the different water treatment methods. Disinfection of various pathogens is often reported either as log removal or percent removal, where 1 log removal is equivalent to 90% removal, 2 log removal is equivalent to 99% removal, etc. Since high disinfection efficiencies are desirable, the disinfection results presented in Tables 1 and 2 are shown as log values. In general, filtration based treatment methods preferentially remove larger pathogens, so size is a critical factor. Typical diameters of pathogen indicators, in µm, are: virus and phage 0. 01 – 0. 10, *E. coli* and bacteria 0. 5-3, *Crypto* 4-7, *Giardia* 9-12. Parasites are generally larger, such as Guinea worm larvae ingested via water fleas that are 0. 2 to 3 mm. For chemical treatment methods, the resistance of different pathogens varies widely. For chlorine at the same dose and contact time, the log removal efficiency of *E. coli* > virus > *Giardia* > *Crypto*. Ozone is a more powerful disinfectant than chlorine, but has a similar relative effectiveness against the various classes of pathogens. Most chemical disinfectants will form by-products with natural organic matter and other elements (such as Br) that are known to be toxic, with many suspected human carcinogens. The concentrations of many of these so-called disinfection by-products (DBPs) in public drinking water supplies are regulated in the U. S. and Europe. For solar light and UV-based methods, viruses and bacteria are readily inactivated. However, dark

repair may occur for some bacteria. The UV doses required for inactivation of *Giardia* and *Crypto* are very high. (U. S. EPA Alternative Disinfectants Guidance)

In developing countries, improved health outcomes are the desired result of improved water disinfection interventions. Reductions in diarrhea incidence observed in populations using the water treatment methods versus untreated water are commonly reported. This information is summarized for household water treatment methods at the end of the chapter. The cited information is not intended to be exhaustive, but rather to provide representative results by which different technologies can be compared.

2. COMMUNITY SCALE WATER TREATMENT

There are a variety of fairly simple and low cost treatment methods that can be used to disinfect water for small communities. The methods included in this review are slow sand filters (SSF), riverbank filtration (RBF), solar methods, UV methods, and membrane units. These methods may also work well in combination, such as a filter-based method to remove turbidity that would interfere with UV disinfection. An overview of each method is provided, followed by a summary of disinfection effectiveness. It is important to keep in mind that all of these community-based systems are at risk of failure if local individuals are not properly trained for maintenance and inadequate user fees are charged to support the maintenance, purchase of consumables (such as diesel fuel for pumps, chemicals) and repairs. In addition, contamination of the water can occur from the effluent of the centralized treatment to the users, either within a distribution system or if water is collected in contaminated containers.

2.1. Slow Sand Filtration

Slow sand filtration is one of the oldest community-scale treatment systems, with documented use dating back more than 170 years. Slow sand filters (SSFs) are used in large, first world cities such as London and Philadelphia, in addition to being used globally in developing communities. A recent example of SSF implementation was the system in Nyabwishongwezi, Rwanda, which was designed to serve 18,000 people and began operating in 2002; the flow rate of the system was not specified (Clarke et al. 2004; Dorea 2008). This system included sedimentation and a gravel roughing filter followed by a SSF. These pre-treatment methods were necessary given that turbidity in the Umuvumba River was as high as 700 NTU, which were typically reduced below 220 NTU by sedimentation, and below 50 NTU after the roughing filters. The plant reportedly operated for two years before it ceased operation due to breakdown of the diesel pumps and inadequacy of the collected tariffs on users. At a site in Mizque, Boliva, SSF are used to treat water from the Uyuchama River after it has passed into an infiltration gallery (similar to bank filtration) to reduce the turbidity from peaks of 400 to 1350 NTU (Sanchez et al. 2006).

Detailed design documentation on conventional SSF was released by the World Health Organization in 1974 (Huisman and Wood 1974). SSF can be sized to provide flow rates suitable for the community by varying the surface area. Reported filtration rates range from 1 to 10 $m^3/m^2/d$. These systems require a significant amount of land, so they are more

commonly used in rural settings. Cost information is summarized in Table 1. The capital cost scales with flow rate treated.

Figure 1 shows a profile view of a typical SSF. SSF systems are generally operated with gravity feed of water through the filter, designed for filtration rates of 2 to 7 m^3/m^2 filter area/d. The gravity flow is fed by about 1 to 1. 5 m of water above the level of the sand; with maximum reported water level of 2 m above the sand bed. The water level is generally kept constant, although it can be allowed to increase over time as the bed clogs. Gravity flow keeps the operating costs low and allows SSF to be used in remote locations without access to power. Research is also being conducted on an upflow variation of SSF (Heller et al. 2006). The sand is packed in a bed with a typical depth 0. 6 to 1. 4 m. The type of sand used will impact the treatment effectiveness. The recommended sand characteristics are: effective size (grain diameter) 0. 1 to 0. 35 mm, minimum grain diameter 0. 084 mm, maximum grain diameter 1 mm, and uniformity coefficient (UC) less than 3. Below the sand is a supporting layer which is typically gravel. The gravel support is typically 3 to 6 layers, with the finest grain size under the sand and the coarsest directly over the underdrain. Each layer is generally 5-12 cm each, with a minimum recommended depth of 3 times the largest grain diameter in the layer. An example of a 3-layer gravel support layer has grain sizes of 1. 2-2. 4 mm, 4. 8-6. 4 mm, and 12. 7-19. 1 mm, with a total depth of 20 to 40 cm. (Fox et al. 1994, Campos et al. 2002; Heller et al. 2006; Kubare and Haarhoff 2010)

The removal of pathogens and particles in a SSF is highly dependent on maturation time. This is due to the importance of the schmutzdecke or colmation layer. For example, only 0. 82 log removal of total coliforms was achieved in a new pilot scale SSF, compared to 4-5 log removal after the SSF had matured for 2 weeks (Heller et al. 2006). Similarly, *Giardia* was not detected in effluent of mature filters vs. 1. 7 log removal initially. To maintain the schmutzdecke, water treatment by the filter should be continuous. The schmutzdecke contains a complex ecosystem of entrapped bacteria, protozoan grazers, nematodes, etc. Very low temperatures may disrupt this ecosystem, although SSF are used in cold climates such as Canada.

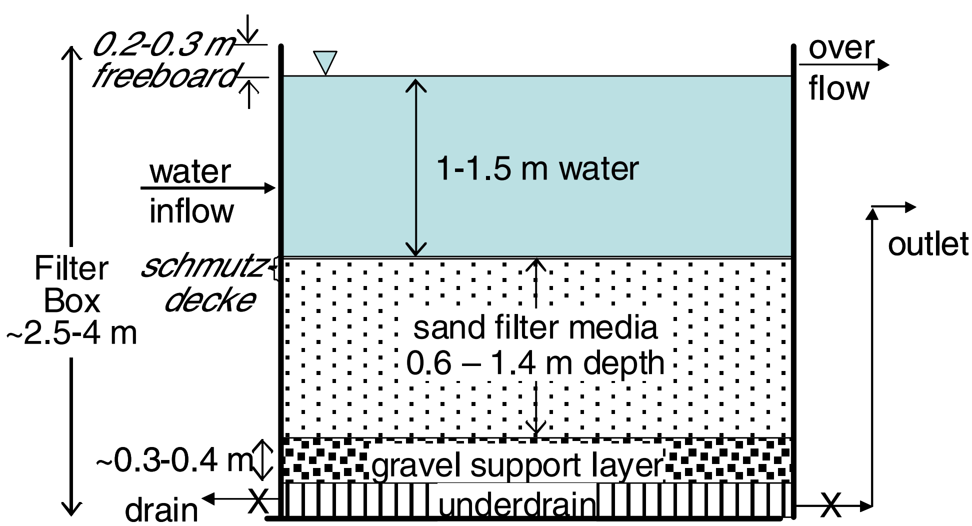

Figure 1. Sketch of a typical slow sand filter

Table 1. Comparison of disinfection effectiveness of selected community-scale drinking water disinfection methods

			Measured log removal efficiency in: L = lab study; P = pilot plant; F = full scale REFERENCE					
Method	Cost, $, *	Flow rate	Total coliform	Fecal coliform	*E. coli*	Viruses (CP = coliphage)	*Giardia*	*Crypto*
SSF	C = 50/ m^3/d [40] LC = 0. 02 /m^3 [40] LC= 0. 21/ m^3 [41]	1-10 m^3/m^2/d	0. 6 – 1. 2 P [12] 0. 6 - 5 [15] 1. 4 ->2. 3 P [6] 2. 0 – 3. 4 P [8] >2 P [5] 4-5 P [4]	1. 8-2. 8 P [8]	1. 8–2. 2 L[11] 2-3 P,F [1] >0. 9->1. 8 P [6]	CP 1. 5-2P [1] CP >2 P[2] Polio 1. 7-4. 5 P [6] CP 2. 6-4. 4 P [6]	1. 2 F[7] 1. 5 P[10] 2. 8 – 5. 5 P [12] 3. 7 - 4. 2 P [8]	0. 3 F[7] 3. 9-7. 1 P [12] 4. 7 P [14] >4. 5 P[9] >5-6 L[1]
RBF	variable	variable	2. 5 F[23] 2. 6 - 5. 2 F[24] >2. 7->3. 6 F[21] >4 F[20]	1. 3 – 4. 2 F[24]	>1. 0 - >1. 7 F[21] >1. 8 F[23]	CP >0. 1->0. 7 F[21] CP 3-6 F [22] 4 F [22*]	>4 F[20] ND [22]	>4 F[20] ND [22]
Solar batch or flow	C = 220 [30] C=2000/ m^3 [40] O =1/m^3 [40]	125 L cap. 1 m^3/d [32]		5 [32] 6 [31]	>4 log @ 4 hr on cloudy day [30] >5-7 @ 2 hr in sun; [30] 7 [31]	>1. 5 F phage [31] 5 [32]	5 [32]	5 [32]

* C = capital cost; O = operation and maintenance cost; LC = life cycle cost of capital + OM discounted

References: [1] Hijnen et al. 2004; [2] Dizer et al. 2004; [3] Heller et al. 2006; [4]Fox et al. 1984, [5]Bellamy et al. 1985, [6]Poynter & Slade 1977; [7]Fogel et al. 1993 (low temperature and non-standard filer sand); [8]Bellamy et al. 1985b; [9]Timms et al. 1995; [10]Vieira 2002 cited by Heller et al. 2006; [11]Unger and Collins 2008; [12]Schuler et al. 1991; [14] Hijnen et al. 2007; [15] Harrington et al. 2001; [20]Gollnitz et al. 2003 ; [21] Partinoudi and Collins 2007; [22]Ray et al. 2002 (ND= not detected, removal efficiency not reported; * "viruses"); [23] Shamrikh and Abdel-Wahab 2008; [24]Kumar and Mehrota 2009; [30] Kang et al. 2006; [31] Fujioika 1995; [32] Safe Water Systems (SunRay 1000); [40] Burch and Thomas 1998; [41] Allen et al. 1988

Most of the pathogen removal occurs in the top of the filter; ~30 cm depth for bacteria and 2. 5 cm depth for *Crypto.* However, Heller et al. (2006) found that *Crypto* penetrated as far as 0. 6 m into a SSF. Penetration depths for viruses are typically assumed to be 0. 8 m (Manz 2004). Cold temperatures have been found to slow the maturation process. Over time, excessive clogging (typically defined as headloss more than 1 to 2 m) may occur which requires that the top 2 to 5 cm of the filter be removed by scraping. SSFs are generally scraped when the inlet water reaches the level of the designed basin depth and/or filtration rates are too slow; this can range from anywhere from 1 month to 1 year. This scraping will be more frequent if the water is higher temperature, contains high solids, the filter is operated with low head, and/or the sand is a smaller size. Due to clogging, it is generally recommended that the water treated by SSFs contain less than 20 NTU turbidity or 50 mg/L TSS. For higher turbidity waters, sedimentation or a roughing filter generally precedes the SSF. Some types of algae may also rapidly clog the filters. Once the schmutzdecke is removed, the filter will require another maturation period during which effluent water quality will improve. This maturation period is generally a few days to 2 weeks.

Table 1 summarizes the disinfection of various indicator species observed in various lab, pilot plant, and field studies. The citations are not intended to be exhaustive, but to give a general sense of SSF performance. High removal efficiencies are commonly observed. Bacteria removals up to 5 log have been observed; removals below 1 log were generally associated with removal prior to the formation of a significant schmutzdecke and/or operation outside of the standard conditions. Up to 4. 5 log disinfection of viruses, including poliovirus and coliphage have been reported. *Crypto* disinfection by SSFs has ranged from 3. 9 to 7. 1 log, with the exception of the Fogel et al. (1993) study. The Fogel et al. (1993) research was on a full-scale SSF in Canada, with sand that did not meet typical design criteria (UC 3. 5) and operated at temperatures down to 0. 5ºC. In addition, their samples were taken after schmutzdecke aging periods of 0. 6 to 13. 6 weeks. The results do reinforce the importance of ensuring that the filter bed complies with the recommended design criteria, the effects of temperature, and allowing development of the schmutzdecke in order to achieve optimal disinfection.

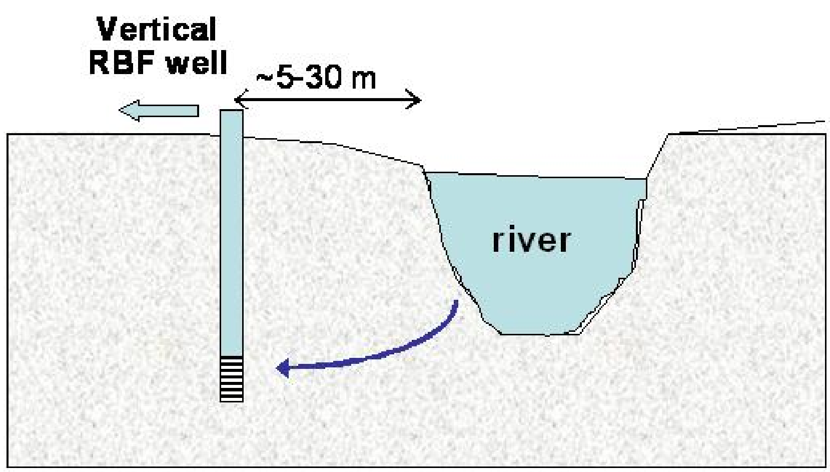

Figure 2. Sketch of river bank filtration (RBF)

2.2. Riverbank Filtration

Riverbank filtration (RBF) has been used since 1870 on the Rhine River, Germany, and it is also widely used by other large cities in Europe. India has been using RBF for more than 25 years (Kumar and Mehrotra 2009), while the documented use of RBF in Egypt and Korea is more recent. RBF also has significant potential for use in China and globally (Ray 2008). RBF places a series of vertical or horizontal wells near a surface water body to extract the water. A simple sketch of a vertical-well based RBF system in shown in Figure 2. RBF uses the natural soil to serve as a filtration and attenuation mechanism to remove pathogens. The natural soil must therefore be of an appropriate composition to remove pathogens. The mechanisms of removal are similar to those at work in SSFs, although the retention times between the river and the extraction wells is generally longer than in a SSF. Alluvial valleys have proved to be compatible with RBF, with typical hydraulic conductivities more than 1 x 10^{-4} m/s. The costs of these systems include drilling or digging the necessary extraction wells, purchasing the pumps, and the power used to operate the pumps.

Kumar and Mehrotra (2009) studied RBF in India via dug wells (brick-lined, 10 m diameter, 8. 7 m deep) and tube wells (22. 6 to 33. 4 m deep). Another recent example of direct use of RBF filtered water without further treatment is in Sidfa, Egypt. The six vertical extraction wells (60 m deep) are located 30 m from the bank of the Nile River and deliver ~6000 m3/d of water via 30-60 HP submersible pumps. The extracted water is a combination of the river water (~70%) and groundwater. The delivered water meets all guidelines for physical, chemical, and microbiological contaminants. (Shamrikh and Abdel-Wahab 2008)

Disinfection achieved by RBF is impacted by the distance from the river to the well, the pumping rate, the aquifer materials, and water chemistry. These factors impact physicochemical filtration. Straining removal of protozoans is based on grain size and shape. Ryan et al. noted that the removal of bacteriophage (PRD1) was influenced by the percentage of ferric oxyhydroxide coating of the quartz sand. U. S. regulations award 0. 5 or 1 log *Crypto* disinfection credit based on the distance of the RBF wells from the bank of 7. 5 or 15 m (25 or 50 ft) (US EPA LT2SWTR). The rule also requires that the system use vertical or horizontal wells, that the aquifer is unconsolidated sand with 10% of the grains <1 mm diameter in size, and that the water turbidity in the wells is <1 NTU. In Sonoma County, CA, and Kearney, NE, RBF systems have been awarded 2-2. 5 log removal credit for *Giardia*. In Casper, Wyoming, site specific data was used to justify 2 log credit for *Crypto* removal.

The disinfection effectiveness of various full scale RBF systems are summarized in Table 1. The RBF systems have been very effective at removing *Giardia* and *Crypto*, which is not surprising given the large size of those protozoans. These protozoans are rarely detected in the effluent from RBF, corresponding to log disinfection exceeding 4 log. Bacterial disinfection exceeding 1 to 5 log has also been achived by RBF systems. In fact, surrogates were generally not detected in the treated water, so the exact removal efficiencies are unknown with the lower limits dependent on the river water quality. For example, in a field study at 4 full scale sites in the US all aerobic spore forming bacteria, total coliforms, and *E. coli* were below the detection limit in the RBF samples; however, male specific coliphage were significantly detected (Partinoudi and Collins 2007). In contrast, some RBF systems have achieved excellent virus removals, with coliphage removal up to 6 log. Not all sites and operating conditions are universally acceptable for RBF. During pilot tests in an arid region of Texas along a canal in the Rio Grande River system, RBF effectively removed protozoans

but was less effective at removing *E. coli* (Langford et al. 2005) For more details on RBF, readers should consult Ray et al. (2003).

2.3. Solar Disinfection

Solar disinfection methods rely on natural sunlight to kill pathogens in the water. Two processes generally combine to achieve disinfection: (1) UV light interacts with cellular DNA and/or other cellular components and causes damage to an extent to render the pathogens non-infectious; (2) heating from the sun raises the temperature to a point that kills the pathogens. Temperatures reportedly required for water pasteurization are typically in the range of 60-65°C. UV dose and temperatures above 40°C have been shown to interact synergistically to achieve disinfection. When the inactivation is primarily due to UV damage of DNA, there is a potential for dark repair of bacteria. Turbidity in the water may protect pathogens by physically blocking the UV light. Therefore, systems that rely primarily on UV damage may require pre-treatment of high turbidity waters through a roughing filter or other method to achieve a suitable turbidity level.

At the community scale, solar disinfection systems are typically designed as a flow through solar thermal pasteurization system. The surface area of contact between the sun and water is an important design consideration. A flow-through SODIS system can treat about 100 L/m^2 on a clear day (Burch and Thomas 1998). There are also commercially available batch system solar pasteurizers, such as the SunRay 1000 from Safe Water Systems which treats ~1000 L/d (Figure 3), equivalent to 175 L/m^2. This system uses a thermal control valve set to open when the water reaches 75ºC; the sunlight conditions determine how long the water remains in the tubes before a new batch of water can be treated. There are reportedly over 1500 SunRay 1000 systems being used in over 50 countries worldwide.

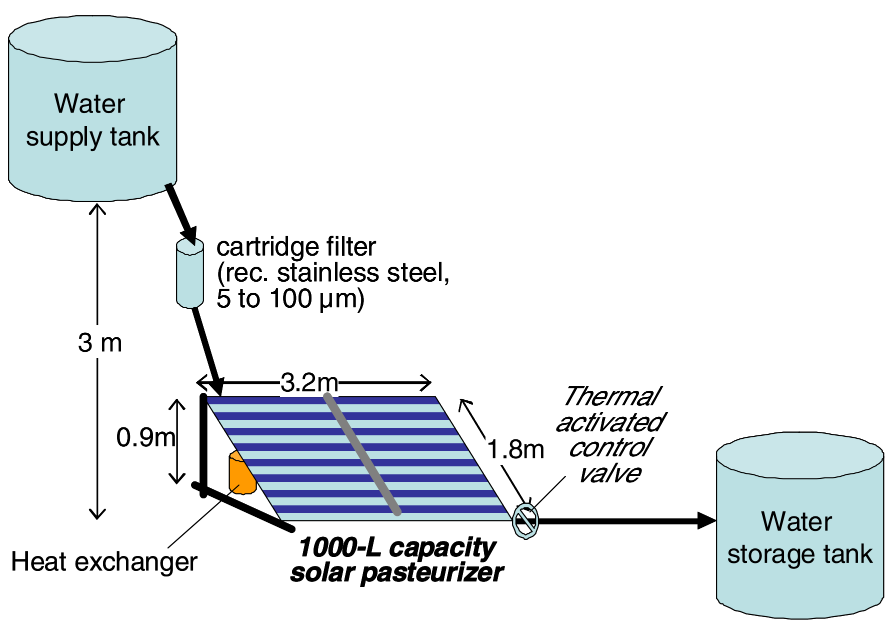

Figure 3. Sketch of community scale solar pasteurizer system, based on the SunRay 1000

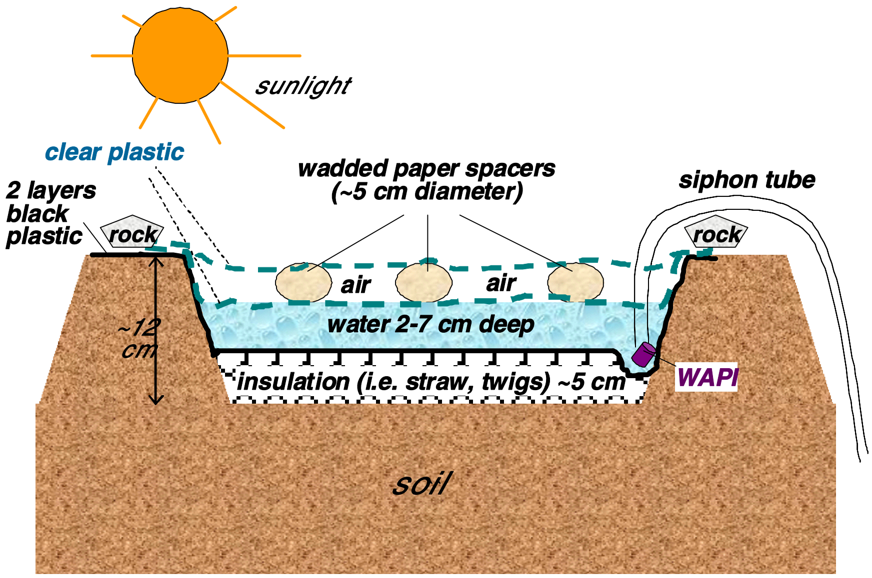

Figure 4. Sketch of profile view of solar pond

Batch systems such as the solar pond / solar puddle (Figure 4) may be more appropriate for developing communities than commercial units. These can be readily constructed from basic materials such as plastic sheets, paper, and straw. The typical water depth of 5 cm will generally reach pasteurization temperatures in 1 day. The area of the system is scaled for the amount of water desired; approximately 50 L per m^2 surface area. In these systems, a WAPI (Water Pasteurization Indicator) is generally used to indicate that sufficient temperature for pasteurization has been reached. A WAPI is simply a plastic tube that contains blue soybean fat that melts at 69°C; when users observe that the WAPI has gone from solid to liquid, the water has reached a sufficient temperature to kill pathogens in the water. The typical cost of a WAPI is ~$2-$3. The WAPI is inserted in the deepest part of the solar puddle, inside the trough, to serve as a conservative indicator. Tests have found that if the pond is properly constructed, the siphon can remove about 90% of the water volume. Because the solar pond relies primarily on temperature for disinfection, turbidity does not significantly impact the pathogen content of the treated water; however, users will find excessive turbidity objectionable. Research is being conducted on whether the addition of titanium dioxide (TiO_2) to serve as a catalyst is beneficial, but results have been mixed and do not yet confirm the benefits of the added cost. Solar disinfection systems are more commonly applied at a household scale; details on these systems are provided later in the chapter.

There is minimal data that has been published on the disinfection effectiveness achieved by community-scale solar disinfection systems. Product literature on the SunRay system reports more than 5 log disinfection of bacteria, viruses, and protozoans, which is not surprising given that the system is driven by pasteurization and that the temperature set-point of the heat valve used is conservative. Full-scale data from systems run by communities over extended time frames is needed.

2.4. Potential High-Tech Methods

Newer water treatment methods gaining widespread use in the developed world such as ultraviolet (UV) light and membranes may be applicable in the future to developing communities. However, at present the energy demands of these systems, training and maintenance requirements, and cost prohibit successful application in developing communities. These methods are briefly described below.

UV treatment methods use electric powered lamps to provide the necessary radiation rather than the sun. In locations where sunlight is variable, these methods increase the year-round reliability of the water treatment systems. Lamps are generally targeted to deliver an "optimal" wavelength range of UV light. Similar to the sunlight based methods, water turbidity is a factor that limits the effectiveness of these methods. Man-made lamp technologies have rapidly improved in the past 10 years, allowing the lamps to target the most damaging wavelengths and reducing their cost. However, these lamps are still commonly mercury vapor tubes and require replacement after 9-12 months of use. Globally, purchasing replacement lamps may be difficult and secondary contamination issues from proper disposal is another concern. UV-LEDs offer future potential, due to rapidly evolving technology which is reducing their costs, increasing their efficiency, and increasing their lifetime (Chatterley and Linden 2009). Gadgil et al. (1998) proposed a UV system that was low cost ($600US), high flow rate (15 L/min), and could treat enough water for 1000 people at an annual cost of $0. 14US per person. This so-called UVWw device developed at Lawrence Berkeley National Laboratory has been widely tested in lab settings and modified through multiple generations to respond to user issues. In lab tests, greater than 4 log disinfection of 10 different pathogens (including 10 different waterborne pathogenic organisms (including *E. coli,*

Salmonella typhii, Vibrio cholerae, Shigella Dysenteriae, and *Pseudomonas aeruginosa*) were achieved. During a field trial in South Africa, 4000 CFU coliform bacteria/100 mL in well water were reduced to below detection; however, over time the treated water quality deteriorated due to contamination introduced in the outlet chamber and outlet pipe. However, the lack of significant adoption of this technology in the subsequent 10 years seems indicative of further problems that have limited widespread use. There was some mention of fouling and cleaning problems. The UV treatment systems could be powered by sustainable energy such as solar panels, wind power, etc.

Membranes with appropriately selected pore sizes are able to remove all pathogens from the water. Reverse osmosis (RO) and nanofiltration (NF) membranes will remove all pathogens, and ultrafiltration (UF) membranes also remove most viruses. The primary limiting factor for their use is the high capital cost of the unit and the high amount of energy required to pump water through the tight material. It has been proposed that in some cases, gravity driven flow will be sufficient (Peter-Varbanets et al. 2009). Photovoltaic (PV) panels to provide the necessary power are also feasible (Bouguecha et al. 2005). From a sustainability perspective, disposal of the brine or retained concentrate is a concern. In warm climates, evaporation-based ponds can be used for brine disposal. In coastal areas, brine can be returned to the ocean. Furthermore, there is concern about fouling of the membranes. Groendkijk and de Vries (2009) described a UF unit with self-generation of hypochlorous acid for cleaning; however, no cost information was provided. A recent review by Peter-Varbanets et al. (2009) found no small-scale membrane systems that were low cost, low

maintenance, and did not require external power. Bouguecha et al. (2005) also conclude that more research is needed to make the technology appropriate. Membranes are frequently incorporated into various commercial water treatment units, such as the SkyHydrant that has been used to treat water in Sri Lanka, Kenya, India, etc. (http://www. skyjuice. com. au/).

3. HOUSEHOLD WATER TREATMENT OPTIONS

Household water treatment (HWT) methods, also called point-of-use (POU) treatment, offer an opportunity for individuals to disinfect their own water. These systems avoid one of the key problems associated with community-based treatment systems: that the water becomes contaminated between the treatment unit and consumption. For example, in Sierra Leone there were no thermotolerant coliform bacteria detected in 8 improved water sources as compared to average counts at the households of 228/100 mL which were detected in 93% of the households tested (Clasen and Bastable 2003). This in-home contamination can likely be reduced by HWT methods. However, there is often significant variation in the quality of these systems between locations due to the variability in locally available materials, variations in the specific designs, and quality control issues during manufacture and/or implementation. A key concern is that individual users must be trained in the correct operation of the systems, and take all responsibility for maintenance. This often results in significant house-to-house variability in the treated water quality. Therefore, the disinfection results measured at real households are almost always more variable and lower than the results presented from laboratory studies. Five common HWT methods (chlorination, chlorination with flocculation, biosand, ceramic water filters, and solar disinfection)will be presented below, including a summary of measured disinfection effectiveness for each method. Note that the ability to measure high amounts of log disinfection under real household use conditions was limited by the source water quality and detection limit of the measurement method. The water quality tests used for samples from home are often only presence/absence based. In many cases, the treated water contained no detectable levels of *E. coli*, for example, but these concentrations were also low in the source water.

3.1. Chlorination

Chlorine is an effective disinfectant that kills bacteria and viruses based on its concentration (dose) and contact time. Protozoans such as *Giardia* and *Crypto* are resistant to chlorination, although some removal is possible with high doses (C = concentration of chlorine) and/or long contact times (t = contact time). In most cases, bleach solution is used as an inexpensive source of chlorine. The background “chlorine demand” of the water will vary based on the amounts of organic and inorganic contaminants in the water. Therefore, the amount of chlorine that must be added to achieve disinfection should account for water quality variability. Chlorine disinfection is also more rapid at higher temperature and lower pH. Residual chlorine often has an objectionable taste and odor to consumers. Chlorination may also form disinfection by-products that are suspected human carcinogens.

The U. S. Center for Disease Control (CDC) promotes the use of chlorination via the addition of a dilute solution of sodium hypochlorite and a contact time of 30 minutes; in concert with user education and water storage practices the CDC calls this the "Safe Water System" (SWS). For "typical" water the recommended dose is 1. 875 mg/L sodium hypochlorite, which represents a Ct of 56. 25 mg min/L; this is doubled for turbid water to 3. 75 mg/L or a Ct of 112. 5 mg min/L. The chlorine is dosed from a concentration of 0. 5-1% sodium hypochlorite that is sold to consumers. The SWS has been implemented in over 30 countries. A study by Clasen et al. (2007) determined that chlorination was the most cost-effective HWT method when resources were limited, as compared to chlorination with flocculation, ceramic filters, and SODIS. They also estimated that chlorination had an average annual mean cost per person of $0. 66. In Zambia, bottles of the bleach sufficient to last 1 month marketed as "Clorin" were sold for $0. 09 (Banerjee et al. 2007). Over a 4-year period of marketing, sales in Zambia reached over 1. 7 million bottles in 2003 and it was determined that a sales price of $0. 18/bottle would be self-sustaining (rather than the subsidized model that had been used). The traditionally recommended SWS storage vessel is a ~20 L plastic container with a narrow mouth, lid, and a spigot.

The disinfection effectiveness of the SWS reported by the CDC (2007) is summarized in Table 2. These data were compiled from a variety of studies with Ct values ranging from <0. 05 to 60 mg min/L. The values appear to represent the intrinsic disinfection achieved in controlled lab studies with water containing <1 NTU turbidity. Results for 10 different bacterial pathogens were reported, and demonstrated a wide range of susceptibility to chlorine. For example, *Burkholderia pseudomallei* and *Yersinia enterocolitica* were among the most recalcitrant, with inactivation of only 2 log and 0. 7-1. 1 log resulting from Ct of 60 and >30 mg min/L, respectively. By comparison, 8 log disinfection of *E. coli* was achieved with a Ct <0. 25 mg min/L. The disinfection of fecal coliform and *E. coli* bacteria by the SWS was much lower in field trials in Pakistan and Guatemala (Luby et al. 1998, 2001; Rangel et al. 2003), at around 2. 2 to 2. 7. This may be due to contamination of the water storage vessel, inadequate contact time, users not doubling the chlorine dose for highly turbid water, or other factors.

Like many HWT methods, there is concern that families will stop using the system over time. Some of this problem is due to the "aid" mentality associated with the systems, which are often given to families by non-profit groups. Education of users generally accompanies the distribution of the SWS, to instruct users on the association of pathogens in water with disease and diarrhea, proper use of the method, etc. However, the users still may not see a need for the system, may not desire the system, and/or find the chlorine taste objectionable. Only 68% of the families in a squatter settlement in Karachi, Pakistan, were still using their 20-L plastic safe water storage vessels two years after distribution of the chlorine and tanks (Luby et al. 2001). The other families reportedly stopped using their vessel because it had broken after more than 6 months of use; the breakage appeared to be caused by sunlight-induced UV degradation of the plastic. The use of UV-stabilized plastics for the water storage container was recommended. In other cases, the simple spigot develop severe leaks over time. Therefore, the users should be educated to plan for both the cost of purchasing the chlorine and periodic replacement of the water storage vessel.

Table 2. Comparison of disinfection achieved by selected household water treatment methods

Treatment Method	Initial Cost, US$	Water yield, L/ unit / d	Measured log removal efficiency in: L = lab study; F = field study; H = real household use [REFERENCE]					
			Coliform	Fecal coliform	*E. coli*	Viruses (CP=coliphage)	*Giardia*	*Crypto*
Chlorination (SWS)	~$0. 5/m^3 - $1. 88/m^3	(20 L)		2. 7 F [32] >4. 3 in 77% homes H [33]	3. 7 to 8 [30] Ave 2. 2 F [31]	2-4 [30]	3 [30]	2 @ Ct 7200 mg min/L [30]
Chlorination/ flocculation (ex. PUR)	Buckets, stirrer $0. 15 /10L	10 L per packet	7 [40] Up to 6 F [41]	>9. 96 L [41]	>7. 9 - >8. 4 L [41] Up to 6 F [41] Ave 2. 97 F[31]	4[40] >4. 6 - >5. 9 L polio [41] >5. 8 L rota [41]	3[40] 3. 6 L [41]	3[40] 4-4. 3 L[41]
Biosand	10-30 [1]	20-40	Hetero-trophs 0. 7 L [11]	0. 45 – 2 F/H [16] 0. 53 F/H [14] 1. 05-2. 5 L[13] 2. 3 F [17]	0. 3–1. 5 L [17] 0. 9 F [16] 1. 2 F [17] 1. 3-1. 7 L[10] 1. 8 L [12] 1. 9-4 L [15]	0. 5 avg; max 1. 3 CP L [15] 0. 5 Hepatitis A L [17] <1 L[10] 2. 1 avg; max >3 echo L [15]	>3 L[10] >3-5 L [11]	>3 L[10] 3. 7 L [11]
CWF	8-35 [2]	12-18	0. 88 H[6] 1. 8->3. 9 L[7]	4. 6->4. 8 L[7]	2. 0-2. 6 L[3] 1. 9 – 2. 6 F[3] 4-7 L[5] 1. 08 H[6] 4. 6->4. 8 L[7]	CP 0. 5-2. 3 L[3] CP 0. 5 – 3 L[5] CP 0. 5-0. 09 L[7] 0. 5-2. 3 *L[8]	4. 3 L[7] >3-3. 5 *L[8]	4. 6 L[7] 3 *L[8]
Solar: SODIS and similar	Negligible for used bottles.	# bottles dependent		1 F 5h, cloud [24] >3 F 2-4. 7h [23] >3. 8 F 2h, sun[24]	>3. 2F 2h,s[24] 2. 2F 5h, cl[24] 5 [20] 5 F 6 h, s[25]	Rotavirus & polio: 3-4 [20] CP 4, 4h s [24] CP 3. 5 F, 6 h, s[25]	3 @ 56ºC, F [22]	>10 hr [20] 0. 98 – 0. 28, 12h, 0-300 NTU [21]

References and Notes: [1] Kubare and Haarhoff 2010; max 30 NTU; [2] Pillers and Diaz 2009; [3] Brown 2007; [4] Mattelet; [5] Van Halem 2006; [6] Kallman et al. 2009; [7] Lantagne 2001a; [8] Bielefeldt et al. 2010; *=carboxylate-coated polystyrene microspheres of similar size; [9] Bielefeldt et al. 2009b;; [10] Stauber et al. 2009; [11] Palmateer et al. 1999; [12] Baker and Duke 2006; [13] Bruzunis 1995; [14] Fewster 2004; [15] Elliott et al. 2008; [16] Earwaker 2006 including summary of other field studies; [17] Stauber 2007 summary of lab and field studies; [20] EAWAG 2009; 6 hr, 40°C; [21] Gomez-Couso et al. 2009; [22] Mtapuri-Zinyowera et al. 2009; [23] Reed et al. 2000, India, South Africa; [24] Rijal and Fujioka 2001; [25] Walker et al. 2004; [30] CDC 2007; [31]Rangel et al. 2003; [32]Luby et al. 2001; [33]Luby et al. 1998; [40] PUR N. D. ; [41] Souter et al. 2003

3.2. Chlorination with Flocculation

A strategy that combines chlorination with flocculation has potential advantages for HWT. The appearance of muddy water due to particulate turbidity can be objectionable to users. This turbidity can also exert a chlorine demand and interfere with disinfection. Both naturally occurring and manmade materials can be used to remove particles and turbidity from water, so called clarification. The chemicals cause the particles (which may include pathogens) to flocculate together into larger aggregates that are easier to remove from water via gravity settling or filtration. Naturally occurring flocculants include *Moringa oleifera* seeds (a tree from Sudan, India, Nepal) and *Opuntia* (a cactus species in Mexico) (Miller and Zimmerman 2009; Beltran-Heredia and Sanchez-Martin 2009).

Commercially available combinations of flocculants with chlorine are commonly used. The CDC (2008b) reported that PUR has been used in over 23 countries. PUR packets (produced by Proctor and Gamble and developed in association with the U. S. Center for Disease Control) are a combination of a ferric sulfate coagulant, an alkaline agent, a flocculant, flocculation aids, and coarse calcium hypochlorite. Each packet has a total mass of 4 g and treats 10 L of water. The contents of the packet must be handled with some care, and kept out of the reach of children, due to contact hazards. To use, water is added to a container, the PUR packet contents are added, the water is stirred for about 5 minutes, and then the water is allowed to settle for ~5 minutes. The clean water is then decanted off the top, sometimes by poured through a clean cloth, into another clean container and is recommended safe to drink after 20 minutes. These packets can be purchased for as little as $0. 15 each, but users must also have access to the containers and stirrers. The annual mean cost per person is about $4. 95 (Clasen et al. 2007). PUR treatment changes the taste of the water, although some users reported quickly adapting to the taste.

As summarized in Table 2, the disinfection of bacteria by the PUR system was very high (~6 to 10 log) in both lab and field trials in Guatemala, Kenya, Pakistan, Philippines, and South Africa (PUR N. D. ; Souter et al. 2003). In particular, the removal of protozoans, such as *Crypto*, was improved over chlorine alone. Virus disinfection was also high at ~4-6 log. Despite potentially successful disinfection, another study found that treated water quality at homes in Guatemala using PUR packets was much worse than would be predicted based on the lab studies (Rangel et al. 2003). Specifically, the initial water quality prior to water treatment intervention averaged 753 to 2553 *E. coli*/100 mL. With distribution of PUR packets, CDC water vessels, and training, the intervention group had 92-93% of the samples with <1 *E. coli* /100 mL; this represented an average of >2. 97 log removal for homes that used the PUR packets and CDC vessels. In homes that used the PUR packets but traditional water storage vessels, the mean *E. coli* concentration was 418 MPN/100 mL, with only 83% of the homes with water containing <1 *E. coli*/100 mL. This indicates that in-home use of contaminated vessels may be a problem. The PUR system can remove water contaminants beyond pathogens. For example, arsenic removal by the PUR systems was >98% in lab tests and >97% in field tests (PUR, N. D.).

3.3. Biosand

The biosand filter (BSF) is a household scale batch water treatment method that utilizes the same principles as SSF. It has been reported that biosand treatment is being used in more than 70 countries by over 500,000 people. (CAWST 2010; Elliott et al. 2008) The schematic in Figure 5 is a typical BSF design, although the specifics can vary significantly. Three sizes of granular media are used: ~6. 5 mm gravel for the underdrain, 2 mm fine gravel for the support layer, and 0. 15-0. 3 mm diameter sand for the filtering media. To operate, a batch of water is added to a depth of ~0. 2-0. 25 m over bed and allowed to drain by gravity flow down to ~0. 05 m over the bed. This filtration time is generally about 2 hours, which is reportedly the typical user "patience" duration. With this type of operation, the filtration velocity was 0. 16-1. 1 m/hr. However, a minimum rate of 0. 5 m/h is recommended, so the slower flow rates that have been reported are likely due to the sand grain size of the media being too small and/or excessive clogging. A water depth of 20-70 mm should be maintained over the sand. The biosand filter is then allowed to rest 6-24 hours before adding another batch of water for treatment. With the standard operation, the daily water production is ~20-40 L. Kubare and Haarhoff (2010) proposed a rational design method driven by the amount of water needed by the user, the container size readily available, sand and gravel readily available locally, and temperature. This allows designs to deviate from standard "rules of thumb" to a customized system. Details on the suggested design, use, and maintenance of biosand filters has been published by CAWST (2010). Design variations of the filter box include a concrete rectangular BSF, plastic cylindrical BSF, and 50-L plastic bucket versions.

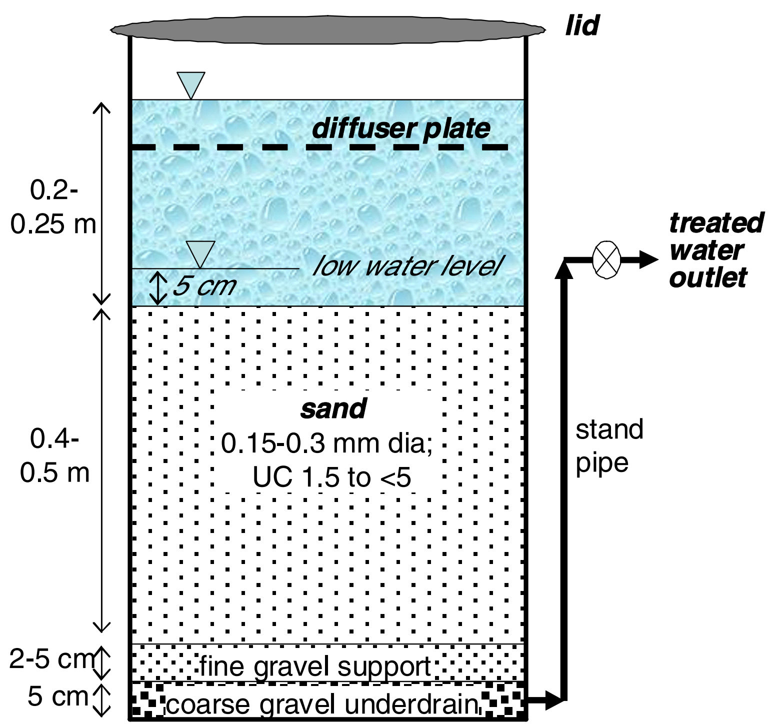

Figure 5. Sketch of cut-away profile view of a biosand filter

Similar to SSF, there is a maturation period needed to establish the schmutzdecke and achieve optimized water treatment. Elliott et al. (2008) found that the disinfection performance was best after 30 days. When the filtration rate drops too low, the filter is manually cleaned. The recommended procedure is to add water to a depth of about 15 cm above the sand, stir the upper layer of the sand, and then discard the top water. Some recommend that the water treated for the first 2 days after this cleaning should be discarded, and in some cases longer periods may be needed to restore the schmutzdecke and optimal water quality. However, Manz (2004) stated that bacterial removal effectiveness was not negatively impacted by cleaning and attributed this to biomass retained on the surface of the sand particles despite the mixing and/or deeper in the sand bed. For users, a time period where they are unable to drink the treated water is unpractical unless they have a large volume already treated and being stored. Air binding in the filter bed may occur during the cleaning process. Entrapped air in the sand will reduce the water filtration rate during operation if not removed. Entrapped air should be removed by allowing treated water to upflow through the filter.

For many biosand systems, users have experienced difficulties associated with the complexity of the system. This confusion and maintenance problems have been shown to negatively impact sustained use of BSFs by families. For example, biosand filters installed near Posoltega, Nicaragua, had a sustained use rate of only 10% (Vanderzwaag 2008). Specifically, 10 of 34 BSFs from 1999 and 14 of 200 BSFs distributed in 2004 were still in use in early 2007. The reasons that the BSFs were not being used included: broken/cracked external concrete structure; a lack of resources to repair the filters; and some families didn't know how to use the filter. Of those still using the filter, all reported that they liked it and believed that it improved both the water quality and their health.

The disinfection performance of biosand filters for different classes of pathogens in lab and field studies and from sampling homes are summarized in Table 2. The disinfection has varied widely, perhaps due to the aging time of the filter (allowing development of the schmutzdecke), water quality differences, and/or filter design and operational conditions. In detailed laboratory studies, Elliott et al. (2008) found that highly superior disinfection of bacteria and viruses was achieved when less than 1 pore volume per day of water was loaded onto the BSF. Field disinfection has varied significantly, with the average removal of fecal coliform bacteria ranging from 64. 4% to 100% in 19 studies in 12 countries summarized by Earwaker (2006); these averaged 92. 5% with a median of 95. 8%. The maximum reported removal of bacteria was 4 log *E. coli* removal in the Elliott et al. (2008) lab study. Virus removal is generally lower than bacteria, and the few studies looking at protozoans have found high removal efficiency. These general trends of BSF disinfection efficiency of protozoans > bacteria > viruses is anticipated based on the filtration-mechanisms which should preferentially remove larger particles. Stauber et al. (2009) also found >3 log (99. 9%) removal of helminths.

Recontamination of the water in storage vessels is sometimes a problem. A field study in Nicaragua found that the average total coliforms in the source water were 10^4 CFU/100 mL, 250 CFU/100 mL in filtered water, but 3000 CFU/100 mL in stored water (Vanderzwaag 2008). Similar results were found with *E. coli*: 120, 6, and 60 CFU/100 mL in source water, filtered water, and stored water, respectively. Baumgartner et al. (2007) simulated various poor-use characteristics to determine the impacts on the disinfection achieved by a plastic biosand filter. They measured significantly better removal of total coliforms during operation

with a 12-hr pause time compared to 36 hr pause time; and that low volume filtration (10 L) was better than high volume (20 L) filtration.

3.4. Ceramic Water Filters

Ceramic water filters (CWFs) are produced by mixing locally available clay soil with a fine organic material (such as sawdust, crushed rice hulls, etc.), shaping to the desired configuration, and firing in a kiln. The ceramic is then typically coated with silver nitrate or colloidal silver to provide additional disinfection capacity. There are multiple configurations of CWFs. The most common, sketched in Figure 6, are: the Potters for Peace (PFP) ceramic pot and similar RDF filter in Cambodia; the round bottom pot; candle filters widely used in India; and ceramic disks. Basic characteristics of these filter variations are summarized in Table 3; these characteristics vary based on the specific production location and other variables.

It is estimated that more than 1 million pot CWFs are in use, which have been produced at over 30 different locations in 28 countries (Pillers and Diaz 2009). The round bottom design modification may simplify manufacture, reduce secondary contamination from placing the flat-bottom filter on contaminated surfaces, and/or reduce breakage during transport. This design is promoted by the non-profit group Thirst-Aid, which reports more than 90,000 filters have been produced and sold by 9 small "factories". The FilterPure round-bottom filter was first produced in 2006 and is now produced in five countries. The FilterPure CWF has a round bottom, colloidal silver mixed into the clay before firing, and a carbon layer within the wall of the filter. Ceramic candle filters have been used in 22 countries, and many are industrially produced by large factories such as Katadyn and Doulton. Disc filters may also be easily produced, but there is a smaller area available to treat the water which reduces the overall filtration rate. The average yearly cost per person has been estimated as $3 among different types of ceramic filter systems (Clasen et al. 2007). The PFP ceramic pot filters have been the most widely studied, and will be reviewed here.

The standard PFP CWF has an internal volume of about 8-10 L, with a bottom inner diameter of ~20 cm, top inner diameter of ~26 cm, and an overall depth of ~24 cm. In the typical use of the CWFs, the ceramic unit is placed in a 5-gallon plastic receptacle that has a tap located near the bottom. A batch of water is poured into the top of the filter and then the water flows by gravity through the filter. Most filters have an initial flow rate of 1-3 L/hour, and this flow rate decreases over time of the water empties into the bottom receptacle. Therefore, users are encouraged to refill the filter 2-4 times/day to increase the water yield. The system should be run with the 5-gallon bucket lid placed on top of the CWF to prevent material from falling in and to minimize exposure to light which can lead to algae growth. Over time, particles removed from the water form a cake layer inside the filter which significantly decreases the flow rates. The inside of the pots are scrubbed with a brush to remove this accumulated material. The frequency of cleaning varies based on the turbidity of the raw water, but is typically every 1 week to 1 month. The CWFs are fragile and at risk for breakage. These in-home breakage rates were about 2% per month in Cambodia (Roberts 2003). Lower cleaning frequency will reduce the risk of breakage during handling. Pre-treatment of the water by settling or cloth filtration is recommended if the initial turbidity of

the water is very high. If the filters are severely clogged, oven drying may also be used as a method to kill pathogens and try to restore the flow rate.

Table 3. Ceramic water filter variations

CWF type:	Pot Filter: flat bottom	Pot Filter: round bottom	Candle filters	Ceramic disks
Location commonly used	Nicaragua, Peru, Ghana, Guatemala, Cambodia, . . .	Thailand; Myanmar; Haiti, Dominican Republic, Uganda, Kenya, Tanzania (FilterPure);	India, Nepal, Brazil, Cambodia	India, Nepal
Flow rates, initial	1-2 L/hr	20-30 L/d	0. 1-1. 5 L/hr	0. 2-0. 9 L/hr
Replacement time, typical	1 – 5 yrs	5 yrs	0. 5 to 3 yrs	6-12 months
Cost, $US	$ 12 – 25 filter and receptacle	$20-30	$2-8/candle + $12-60 for filter unit	$4-$21
Concerns	Silver leached out after ~1 yr reduces disinfection; crack develops but filter still used; breakage	A lot of the silver not in contact with water;	Proper attachment to prevent leaks; replacement; clogging	Disk attached using white or gray cement to upper container; leaks along this interface a concern

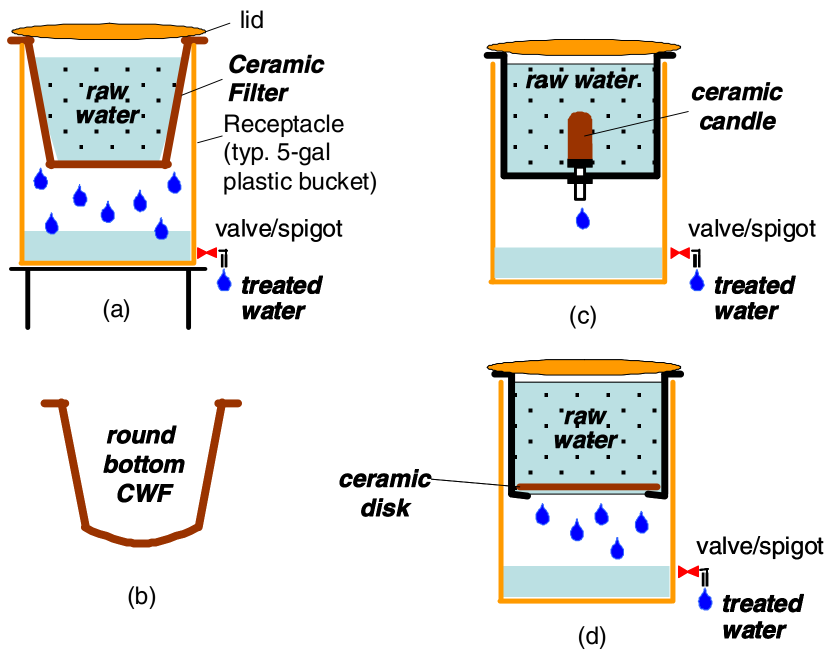

Figure 6. Ceramic water filter variations. (a) Potters for Peace flowerpot shaped; (b) rounded bottom shape; (c) candle filter; (d) ceramic disk

There are two primary mechanisms of disinfection in CWFs: physical removal and inactivation. Pathogens may be physically filtered out of the water by straining from the small pores in the filter and the filter cake that accumulates inside the filter. Bacteria and viruses can also be removed from the water by surface association with the ceramic, which will be impacted by the charge on the ceramic, pathogen surface characteristics, and water chemistry. Studies are underway to determine if higher flow rates will still achieve sufficient pathogen removal, but it is of concern that the larger pores that cause higher flow rates would be less effective at filtration-based pathogen removal.

The applied silver may inactivate pathogens. Ionic and nanoscale silver have been shown to kill bacteria and viruses. The disinfection effectiveness of silver against protozoans has not been well documented; however, these larger pathogens are readily removed by filtration. It is unclear if the colloidal silver attached to the ceramic surface exerts similar pathogen inactivation mechanisms as suspensions of ionic and/or nanoscale silver. Oyanedel-Craver and Smith (2008) postulated that the silver on the ceramic creates reactive oxygen species that inactivate pathogens. The silver associated with the filter may inactivate the pathogens that pass through the filter pores, inhibit bacterial growth in the filter (bacteriostatic), or exert other effects that benefit disinfection. Over time the applied silver leaches out into the treated water at low concentrations. These concentrations are well below the health-based limit of 100 ppb. But the silver leaching off is of concern due to reduced capacity of the filters to disinfect water over time. It has been estimated that the silver will fully leach out of the PFP CWFs after 1 to 2 years of continuous use.

A variation on the simple CWF promoted by PFP is the FilterPure version. This filter differs in 3 main ways: (1) silver is added to the clay and organic material before firing; (2) charcoal is integrated into the center of the filter; and (3) the bottom is rounded rather than flat (Figure 6b). It is uncertain which variation of the CWF is superior in terms of disinfection efficiency. The charcoal layer may add a variation in surface charge compared to the ceramic that may improve the removal of some pathogens such as viruses. The silver integrated into the ceramic may also provide different long-term treatment efficacy. However, no independent data that directly compared the different filter types has shown a significant improvement in disinfection performance (Ballantine and Hawkins 2009; Napotnik et al. 2009). Other variations on the CWF include the incorporation of iron or aluminum oxides into the clay before firing, which increased the removal of bacteriophages (Brown and Sobsey 2009).

CWFs have achieved excellent disinfection of bacteria in many laboratory experiments (summarized in Table 2). Longer term lab tests have found diminished treatment effectiveness over time, in particular when the silver has been depleted. For example, in laboratory experiments where six CWFs from Nicaragua were loaded with water highly contaminated with *E. coli* (~10^6 CFU/mL), the disinfection efficiency in the first batch of water treated ranged from 2. 9 to 5 log, but by the third batch of highly-contaminated water treated this disinfection had dropped to 0. 1 to 4. 3 log (Bielefeldt et al. 2009). Controlled field tests have also found high disinfection of bacteria (Table 2). However, water samples collected from the homes of users have shown highly variable treatment efficiency. Disinfection of viruses is generally lower and less efficient than bacteria. Protozoans have been poorly studied but appear to be easily removed due to their large size.

In some cases, the water treated by CWFs was more contaminated that the source water Lantagne 2001b and others). This problem has generally been attributed to contamination of

the bottom receptacle. The recontamination issue in the water storage receptacle is a similar problem with the BSF. In the field study by Kallman et al. (2009) in Guatemala, 10% of the samples contained higher concentrations of bacteria in the treated water. In Brown's (2007) study in Guatemala, 17% of all filtered samples had higher concentrations of *E. coli* than the influent water; some samples contained as much as 3 log higher *E. coli*. Laboratory studies by Bielefeldt et al. (2009) also found contamination of clean water after the filter had treated a few batches of water highly contaminated with *E. coli*. This contamination was not due to the bottom receptacle, but rather bacteria coming off the filter itself. Therefore, periods of highly contaminated water treatment may contaminate the filter to the extent that bacteria "break through" the filter. Other user problems may also compromise the treated water quality. Baumgartner et al. (2007) found that over filling the CWF significantly reduced the removal of total coliforms and *E. coli* by the system from 99. 4±0. 2% and 99. 8±0. 2% under normal operating conditions, respectively, to 47. 8±10. 4% and 48. 7±11. 6% when overfilled, respectively.

3.5. Solar Disinfection

A number of different household scale water treatment methods can use the sun, either for disinfection by UV and/or heat. The basic principles are the same as those described in the community-scale solar disinfection section. Table 4 compares common solar-based HWT methods.

SODIS is the most common method used at a household scale for drinking water treatment. SODIS is promoted by EAWAG and used in an estimated 33 countries by over 2 million people. It has the lowest cost among HWT methods, estimated at an annual mean cost per person of $0. 63 (Clasen et al. 2007). A clear plastic (or sometimes glass) bottle is filled about 80% full, shaken to oxygenate, placed on a metal rooftop or black surface, and allowed to sit in the sun. The combination of UV light and heat achieve disinfection. Although the temperature is below that needed for pasteurization, the elevated temperature does result in improved disinfection efficiency. The higher range of the reported temperatures in Table 4 have been achieved at field sites on sunny days, while the lower end of the temperature range is typically associated with cloudy days or cold outside temperatures. In many cases the bottom half of the bottles are painted black. There are common rules of thumb that are used to determine the amount of time the water must sit before it can be safely consumed. For example, the water should remain in full sun for more than 6 hours or 2 days under cloudy conditions (CDC 2008d). The primary disadvantages of SODIS are the low quantity of water produced; interference of turbidity; user uncertainty on the amount of time required to achieve disinfection (which are longer on cloudy days and at low temperatures); and lower user satisfaction associated with drinking warm water.

For treatment methods that rely primarily on UV, most studies report a reduction rate in pathogen concentrations as a function of light exposure, rather than an overall generic log removal. This is because the log removal will be significantly impacted by the solar intensity, temperature, and other water quality parameters (notably turbidity). Sunlight contains a wide range of wavelengths, encompassing UV-C, UV-B, UV-A, visible light, and infrared up to about 2500 nm at sea level. In contrast, UV-lamps used for disinfection emit a more narrow

range of wavelengths. It is commonly considered that the most effective wavelengths for disinfection are 260-265 nm, which is the maximum absorption range for DNA. However, laboratory studies have found different optimum wavelengths for inactivating different bacteria, such as 265 nm for *E. coli*, 270 nm for *Bacillus subtilis*, 271 nm for *Crypto* oocysts (Kowalski 2009). Bosshard et al. (2009) has also found that UV-A will breakdown various membrane functions in *E. coli*.

The solar disinfection resistance (SDR) of pathogens relative to *E. coli* (with a resistance of 1) was reported by Gill and McLoughlin (2007); most bacteria had a SDR ranging from 0. 4 to 6 (*Enterococci* sp.) and *B. subtillus* were 6. 8-10. 4 (due to spore formation); MS-2 phage and Poliovirus SDR were 1. 8-2. 2; and the protozoan *A. polyphaga* SDR was 3. 1. In a study in Spain and Bolivia with strong natural sunlight, greater than 4-log reduction of *E. coli* was achieved within 90 minutes; other bacteria had inactivation times of 20 – 150 minutes (Boyle et al. 2008). More than 16 hours of exposure only killed 96% of *B. subtilis* endospores, indicating that spore-forming bacteria may survive typical SODIS treatment. In a study simulating SODIS treatment using a xenon arc lamp providing a solar irradiation of 830 W m^{-2} at 40ºC, the time to fully render *Crypto* and *Giardia* non-infective were 10 hours and 4 hours, respectively (McGuigan et al. 2006). In other experiments, 1 log *Crypto* inactivation was achieved within 1 hour in tap water; increased dissolved organic carbon inhibited disinfection (King et al. 2008).

Although some concerns have been raised about the human health risks associated with plasticizers leaching out of plastic bottles into the water, a recent study by Schmid et al. (2008) found that these risks are negligible. Specifically, the amount of DEHA (di(2-ethylbexyl)adipate) and DEHP (di(2-ethylhexyl)phthalate) that leached out of 15 different used or reused colorless polyethylene terephthalate (PET) bottles of different origin (Honduras, Nepal, Switzerland) after 17 hours in sunlight or shade were less than 0. 046 and 0. 71 µg/L, respectively. This was similar to the range reported in bottled water in first world countries and corresponded to a minimum safety factor of 8. 5 and negligible carcinogenic risk of 1 in 2. 8 E7 for DEHP.

Table 4. Comparison of solar disinfection methods

	Volume	Water Temp, °C	Examples of time to reach target disinfection
SODIS	PET or glass bottles, typically 1-2 L each	30-48	6 h in full sun; 2 days if cloudy
Family Sol*Saver System (FSP)	Double walled black PE collector *or* UV transmittable cover	65 + 56	3 hr >3 log *E. coli* 2 hr >3 log *E. coli*
Solar Puddle	variable	69 (WAPI)	Not reported
PAX flow through tubing coiled in solar box cooker	1. 5 L	83. 5	1 to 2 hrs to reach pasteurization temperature

http://www. hedon. info/TheSolarPuddle-ANewWaterPasteurizationTechnique
http://www. she-inc. org/docs/90. pdf

Similar to other HWT systems, there is sometimes low uptake of the SODIS technology into the community as indicated by sustained use. In 18 countries the sustained use of SODIS ranged from 20-80% 1-year after the implementation of SODIS training (Meierhofer and Landolt 2009). During a study in a peri-urban area of Kathmandu, Nepal, only 10% of the households routinely disinfected their water using SODIS (Rainey and Harding 2005) Factors that were found to increase the likelihood of sustained use included: local availability of PET or glass bottles; long-term, sustained visits to trained users over several months; locally respected people in the community promoting SODIS; social pressure and highly visible use of SODIS prevalent in the community; and integration of SOIDS into official educational practices (Meierhofer and Landolt 2009).

To overcome the water quantity limitation, a household scale batch treatment system, the so-called Family Sol-Saver System (FSP) can be used. It works by the same processes as SODIS but flat rectangular plat (51x122x8 cm) produces about 3. 5 gallons of water. If the water contains high turbidity, simple pre-treatment methods such as settling or cloth filtration may be needed prior to SODIS.

Other solar-based HWT systems rely primarily on heat and pasteurization. The PAX system is a batch/flow through device where ~15-18 m of plastic tubing is painted black and coiled inside a standard solar box oven. A simple car thermal valve is added that opens when the temperature is ~83. 5°C, which is more than sufficient to ensure disinfection of the water. Water pasteurization is normally associated with a water temperature of 65°C for 6 minutes or more. These solar ovens typically have minimum internal dimensions of 15 cm long x 15 cm wide x 8 cm depth, and are constructed of cardboard or wood and foil. The system costs about $50 and can treat about 4-6 gallons of water/day, based on tests in Pakistan (Metcalf 1994). The solar pond described earlier can also be scaled down for household use.

Table 2 summarizes a few of the reported disinfection results from solar-based HWT. Due to the range of solar conditions, temperature, water turbidity, etc. the disinfection efficiency of solar treatment methods have varied considerably. Relative resistance to UV has been measured as inactivation rates in cm^2/mJ. These data are generally based on lab studies with UV-light in a narrow wavelength range rather than natural solar radiation. Based on this information, the highest UV disinfection resistance appears to be viruses and bacterial spores > protozoan (oo)cysts > bacteria. Dark repair of UV-damaged DNA (due to UV-C) has been reported for some bacteria, but this appears to be less relevant for disinfection by sunlight or UVA which inhibit the respiratory chain. For example, there was no regrowth of *E. coli*, *Salmonella typimurium* and *Shigella Flexneri* found when SODIS-treated water was stored in the dark (Bosshard et al. 2009).

4. Health Impacts of Water Treatment

Because most water treatment studies only measure the disinfection of selected indicator organisms, the true test of the disinfection effectiveness should be evident in improved health outcomes. However, this is particularly challenging due to interrelated factors of water treatment and hygiene. For example, no clear relationship was found between point-of-use water quality and general diarrhea in a post-hoc correlation of 16 published studies by Gundry et al. (2004). The same study did, however, find that water quality was correlated to cholera

and that water treatment interventions significantly reduced diarrhea incidence. Nevertheless, some data regarding the health impacts of various HWT methods are summarized in Table 5, reported in terms of decreased diarrhea incidence. It has been estimated by the World Health Organization that about 1. 8 million people die each year from diarrheal disease. Diarrhea can be caused by any number of viruses, bacteria, protozoans, and/or intestinal parasites (such as Guinea worm). In some cases the infectious dose of these pathogens may be very small. Certain populations, such as HIV-positive people, may be more susceptible.

Hunter (2009) conducted a meta-regression of health outcomes data from 28 studies on 39 different household water treatment interventions. He determined that the CWF was significantly more effective than all of the other treatment methods (biosand, chlorine and SWS; combined coagulant-chlorine; and SODIS). The key variables that impacted the effectiveness of the interventions were: duration of study follow-up; whether or not the study was blinded; and use in an emergency setting. Further, after 12 months SODIS, chlorination-SWS, and coagulation-chlorination had no more beneficial effect than the standard reporting error in unblinded studies. Hunter concluded that all methods except CWFs had "poor if any longterm public health benefit". These are disappointing results, and contrast with many other studies (summarized in Table 5), potentially due to the strict nature of the Hunter (2009) study to eliminate recall bias from the data sets. Hunter's results indicate the importance of carefully interpreting the results from health studies, including controls, etc. Using the data shown in Table 5, almost all of the HWT methods showed some decrease in diarrhea incidence, with no method clearly superior to the others. Improved health outcomes beyond diarrhea have been found due to HWT. In three un-blinded studies summarized by Gundry et al. (2004), lower cholera incidence was associated with: SODIS in children less than 5 years of age; all users of chlorination and improved storage (SWS) and alum potash (a form of flocculation).

Table 5. Diarrhea reduction associated with household water treatment methods

Treatment Method	% diarrhea reduction	Population	Location	Reference
Chlorination	22 – 84 48	Rural, urban, adults, children, HIV 166 households	Summary of many Kitwe, Zambia	CDC 2008a Quick et al. 2002
Coagulation-Chlorination	16 - >90	Rural, urban, refugee camps, adults, children	Summary of many	CDC 2008b
Biosand	62 47	Children ≤15 yrs old ~900 people in ~180 HH	Along River Njoro, Kenya; Dominican Republic	Tiwari et al. 2009 Stauber et al. 2009
CWF	60-70 49 72	Unspecified All ages; 395 people + 403 control Children <5 yrs	Summary of many Cambodia Bolivia	CDC 2008c Brown et al. 2003 Clasen et al. 2004
SODIS	9-86 Not significant 40 16-57% 13-20%	Variable Children <5 yrs Children <5 yrs Children <5 yrs Variable	Summary of 4 randomized trials Rural Bolivia India Kenya, Bolivia, Uzbekistan Pakistan	CDC 2008d Mausezahl et al. 2009 Rose et al. 2006 Meierhofer & Landolt 2009

5. Conclusion

There are a number of different water disinfection methods that may be suitable for use in low income developing communities. The most appropriate treatment will vary based on the local climate (temperature and sunlight), local water quality (turbidity, organics, pathogens present), and user specific concerns (tolerance of chlorine taste, etc). Local materials, skills, culture, and financial resources should be considered. The intrinsic effectiveness of the method measured in laboratory studies is often much higher than the disinfection observed in the field at full-scale community systems and/or in individual households. Poor user training and financial limitations for maintenance contribute to these difficulties. In addition, the initial effectiveness of some methods may decrease over time. This can be an important effect in both lab and field studies. History has shown that user input and demand is critical for success. Many of the "aid" models of giving users a water treatment device have failed. Non-technical factors are equally as important as technical factors in determining the actual disinfection that users will experience in a specific setting. Sobsey et al. (2008) critically evaluated HWT methods based on performance and sustainability criteria and determined that BSF and CWF were most effective. Others will argue that individuals are unreliable to maintain HWT systems and that community-scale treatment should be used. But this poses its own problems including contamination in the distribution system. Each of the methods presented in this chapter may be effective in particular settings, and all also have the potential for failure.

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